Metal Matrix Composites for Ordnance Applications

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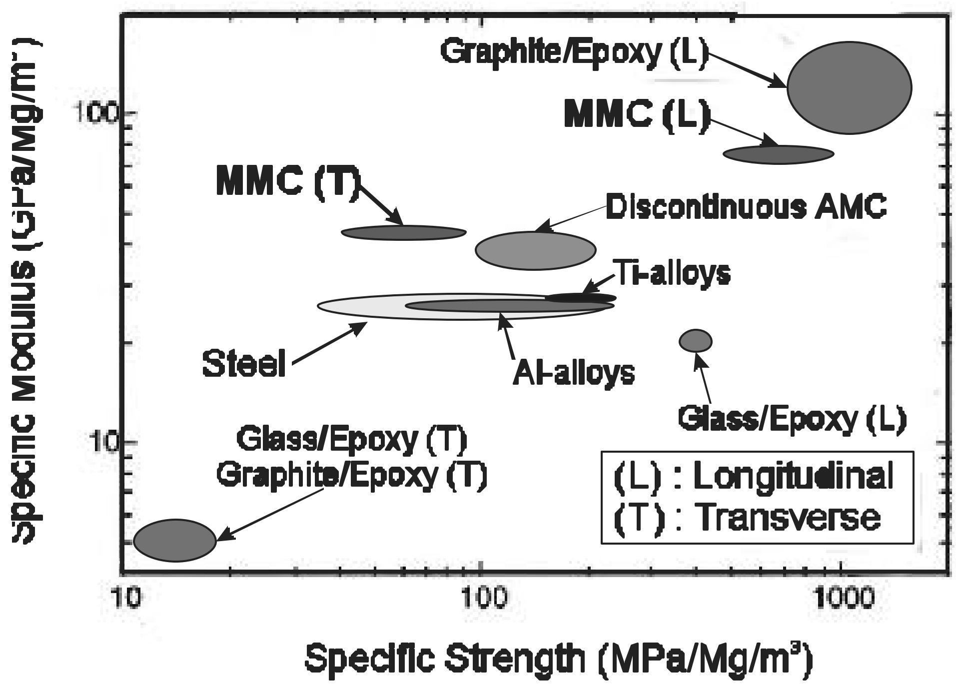
Metal Matrix Composites for Ordnance Applications
Outline

- Motivation
- Background
  - ➔ Army History
  - ➔ 3M DARPA Program
- Development of Analysis Methodology
  - ➔ Lamina or Ply Level
  - ➔ Laminate Level
- Application - Projectile Shell
- Conclusions

Motivation

- **Outstanding Mechanical and Thermal Properties**
  - Specific fiber direction stiffness comparable to carbon/epoxy
  - Transverse and shear properties much greater than carbon/epoxy
  - Very high compression strength (~500 ksi)



- **Useful Physical Properties**
  - High thermal conduction (~5 times graphite/epoxy)
  - Low CTE
  - High melting point

- **Objective Force has Critical Need for Lightweight, High Performance Materials**
  - Optimized Projectiles
  - Lightweight Gun Tubes

Background

- **Metal Matrix Composites have drawn strong interest from the Army for over 30 years**
  – AMMRC, MTL, BRL, and ARL have funded research since 1960's
  – Over 60 reports in this area

- **Diverse applications have been investigated**
  – Tank track shoes
  – Helicopter transmission casings, landing gears, skids and wear pads
  – Ballistic missile structural components
  – Lightweight assault bridging components
  – .50 caliber machine gun components

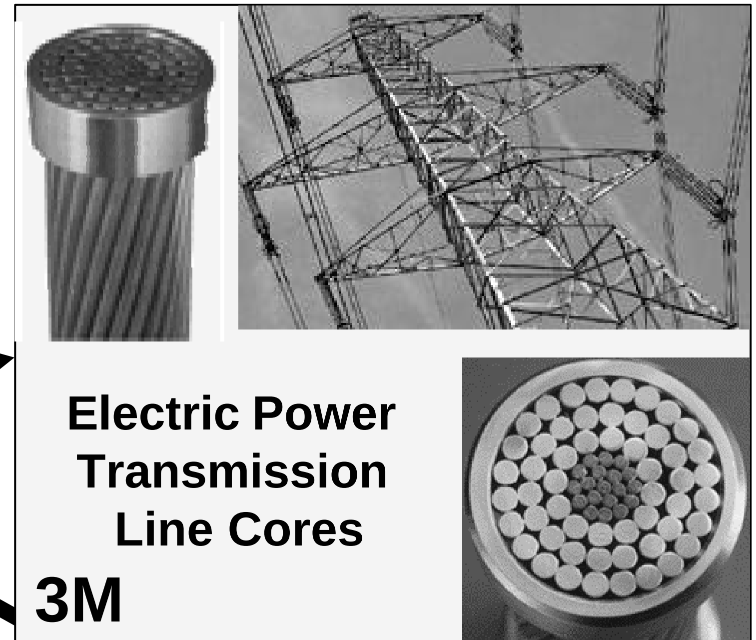
- **Widespread use has been limited by**
  – High material costs
  – Lack of a reasonable production base
  – Lack of design tools

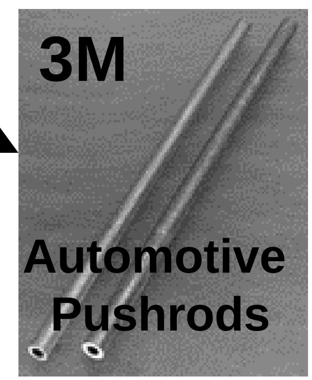
3M Production Base

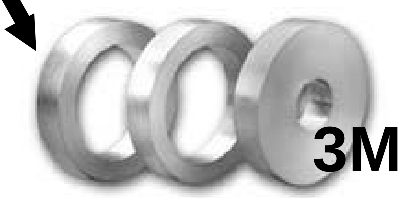
Defense Advanced Research Projects Agency DARPA

3M DARPA
Program
($140M)

Nextel Alumina Fibers







Flywheels

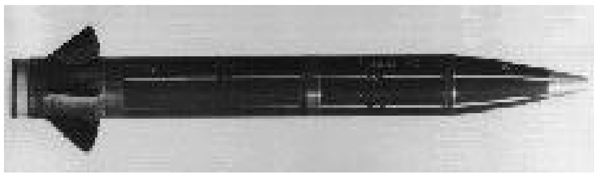
Low-cost (<$100/lb)

Large production base

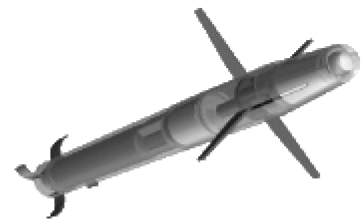
Outstanding properties

Metal Matrix Composites for Ordnance Applications (STO IV.MA.2001.01)

Objective: Develop metal matrix composite technology for more lethal projectiles and lighter armaments for FCS



TOTAL
$2150K



<u>Pacing Technologies</u>:

- **Artillery Projectile:**
  - → **Joining Technology**
  - → **Processing**
- **Gun Barrel:**
  - → **Thermal Fatigue**
  - → **Processing**

<u>Warfighter Payoffs</u>:

- **Enhanced Lethality and Survivability**
- **Lightweight projectiles with greater payload capacity**
- **Lightweight armament systems**

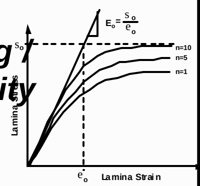
Projectile shells 50% lighter than steel shells with 67% less parasitic volume than polymer matrix composite shells; Gun barrels 50% lighter than steel

Metal Matrix Composites for Ordnance Applications (STO IV.MA.2001.01)

FY01	FY02	FY03	FY04	FY05	FY06	FY07

TRL=3

Material Modeling / Analysis Capability

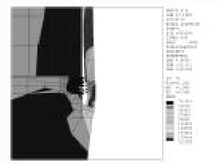


METRIC:

Thermal and Mechanical properties validated and modeling capabilities developed

TRL=4

Sub-Scale Testing



METRIC:

Joining technology developed, non-destructive evaluation and fatigue tests completed

TRL=3

Application Down-select

METRIC:

Material properties and optimal impact determine application:

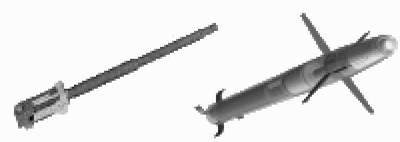
- **lightweight projectile shell**

or

- **lightweight barrel component**

TRL=5

Prototype Demonstration



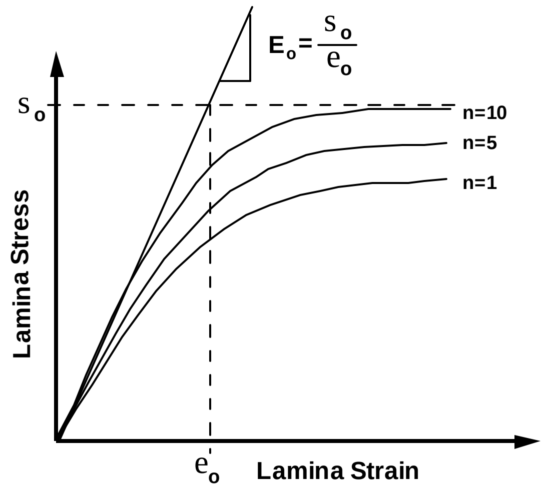
METRIC:

- **Projectile shells 50% lighter than steel shells with 67% less parasitic volume than Polymer Matrix Composite technology or Gun barrels 50% lighter than steel**

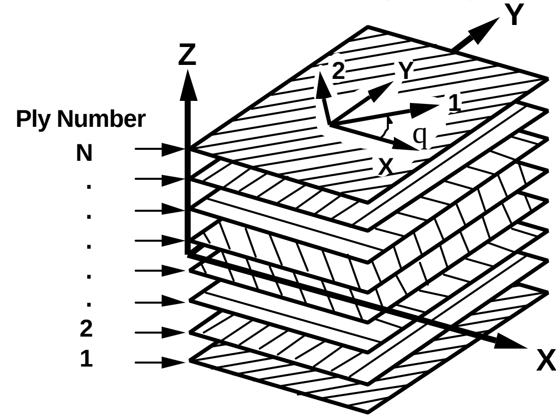
- **Transition to Multi-Role Armament & Ammunition ATD**

Nonlinear Composite Modeling - Approach

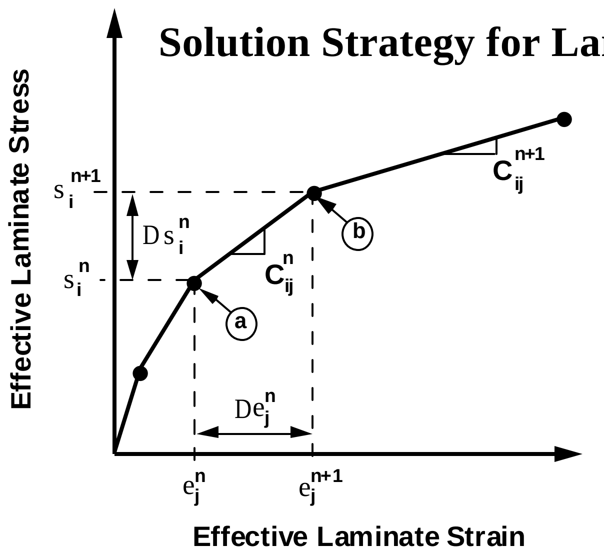
Characterize Lamina Level Properties



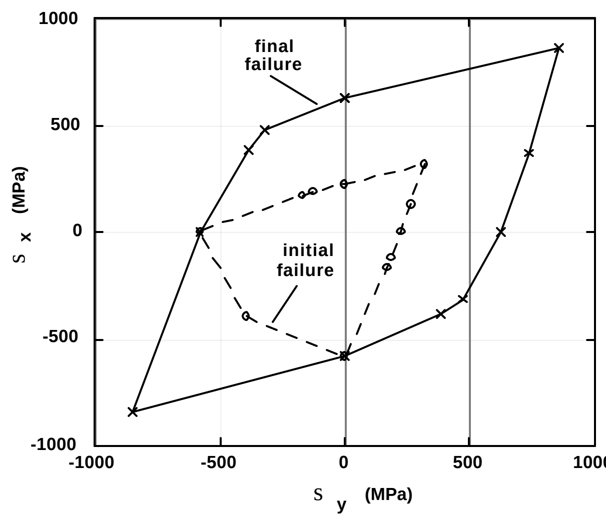
Allow for Arbitrary Lay-Ups



Solution Strategy for Laminate

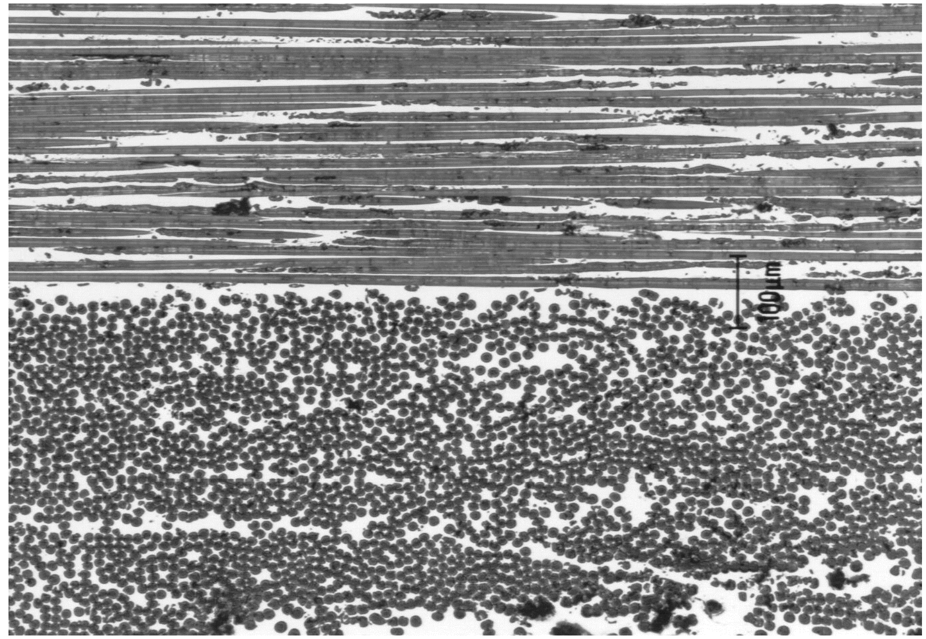


Failure Prediction for Multi-Axial Loading

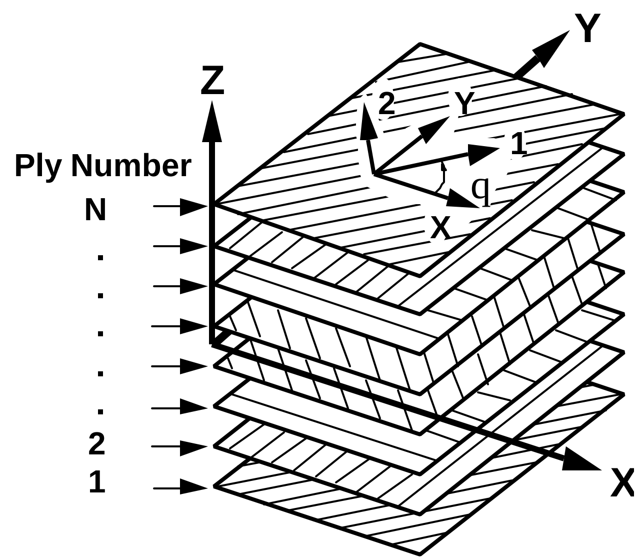


Composite Mechanics

- **Lamina or Ply Properties**
  - –Individual ply or layer
  - –Properties dominated by
    - » Fiber
    - » Matrix
    - » Interface
  - –Nine failure modes

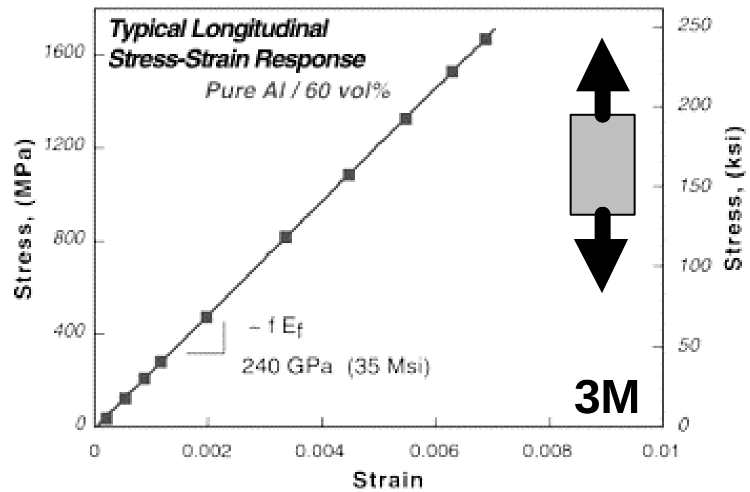


- **Laminate Properties**
  - –Series of lamina
  - –Properties dominated by
    - » Lamina properties
    - » Order and Orientation of lamina



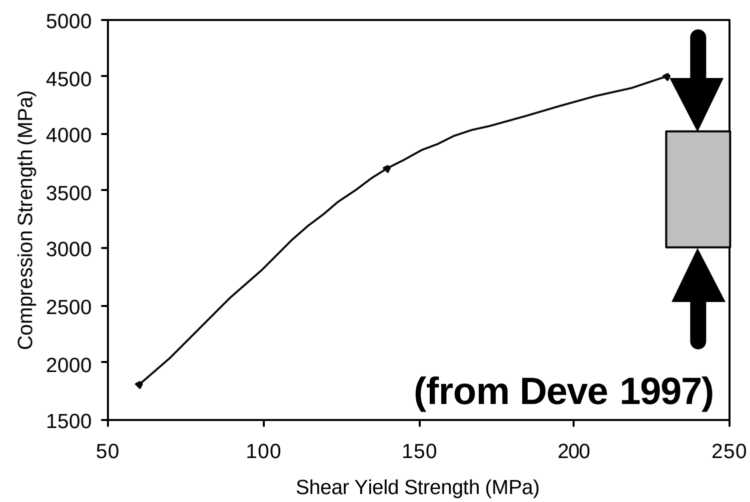
Lamina Properties

- **Tensile Properties**
  - –Dominated by fibers
  - –Strength and Stiffness are linearly proportional to the fiber volume fraction



- **Compression properties**
  - – Stiffness is proportional to fiber volume fraction
  - – Strength is dominated by shear yield strength of matrix

$$\sigma_c = G\left[1 + n\left(\frac{3}{7}\right)^{\frac{1}{n}}\left(\frac{F}{(n-1)\gamma_y}\right)^{n-\frac{1}{n}}\right]^{-1}$$



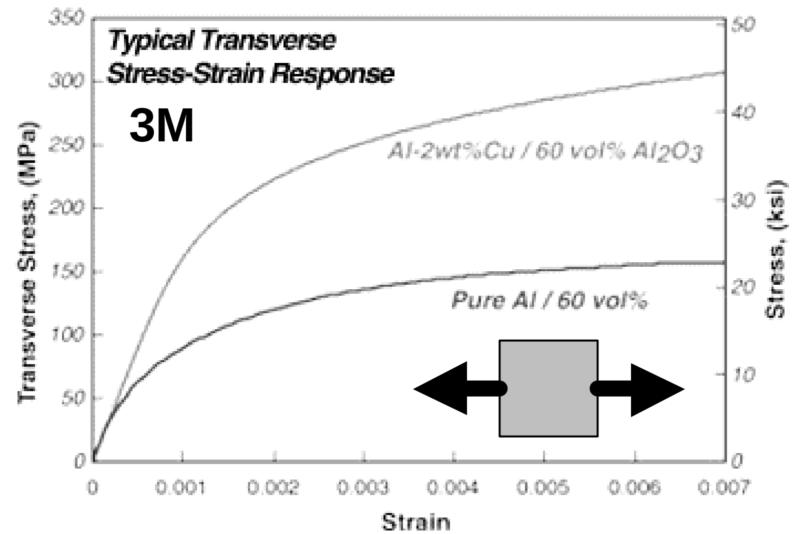
Transverse and Shear Lamina Properties

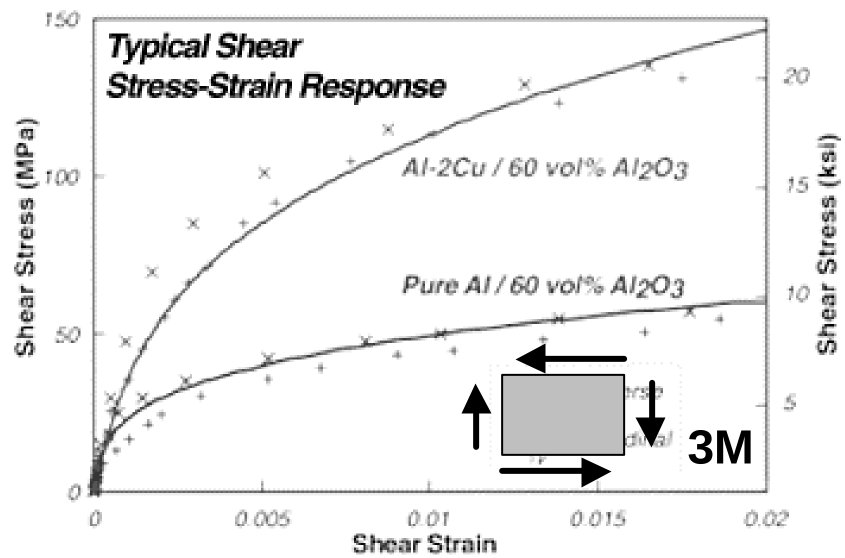
- **Stress-Strain Response**
  - Initial modulus defined by rule-of-mixtures

$$\frac{1}{E_c} = \frac{V_f}{E_f} + \frac{V_m}{E_m}$$

  - Overall response is non-linear and dependent on matrix

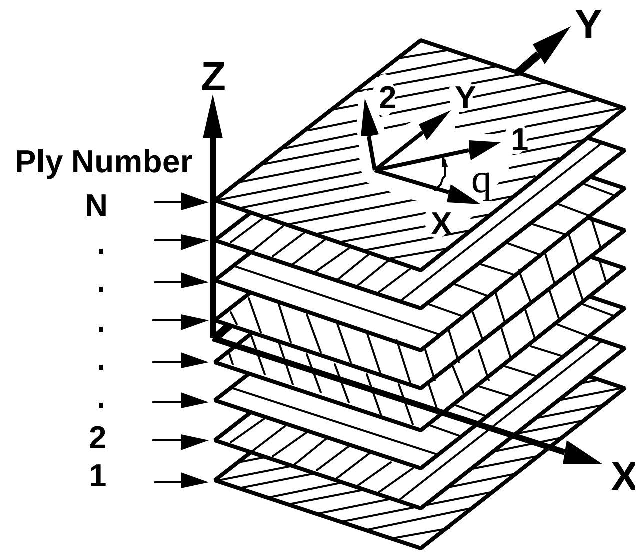
- **Transverse and shear properties more important in MMCs than PMCs**
  - For MMC E_T = 138 GPa
  - For PMC E_T = 7 GPa





Laminate Mechanics

- **Classical laminate mechanics can be used to accurately predict the initial linear-elastic behavior of MMC laminates**
- **More advanced methodologies are needed to predict full stress-strain curve**
  - Non-linear shear and transverse properties
  - Progressive failure of lamina



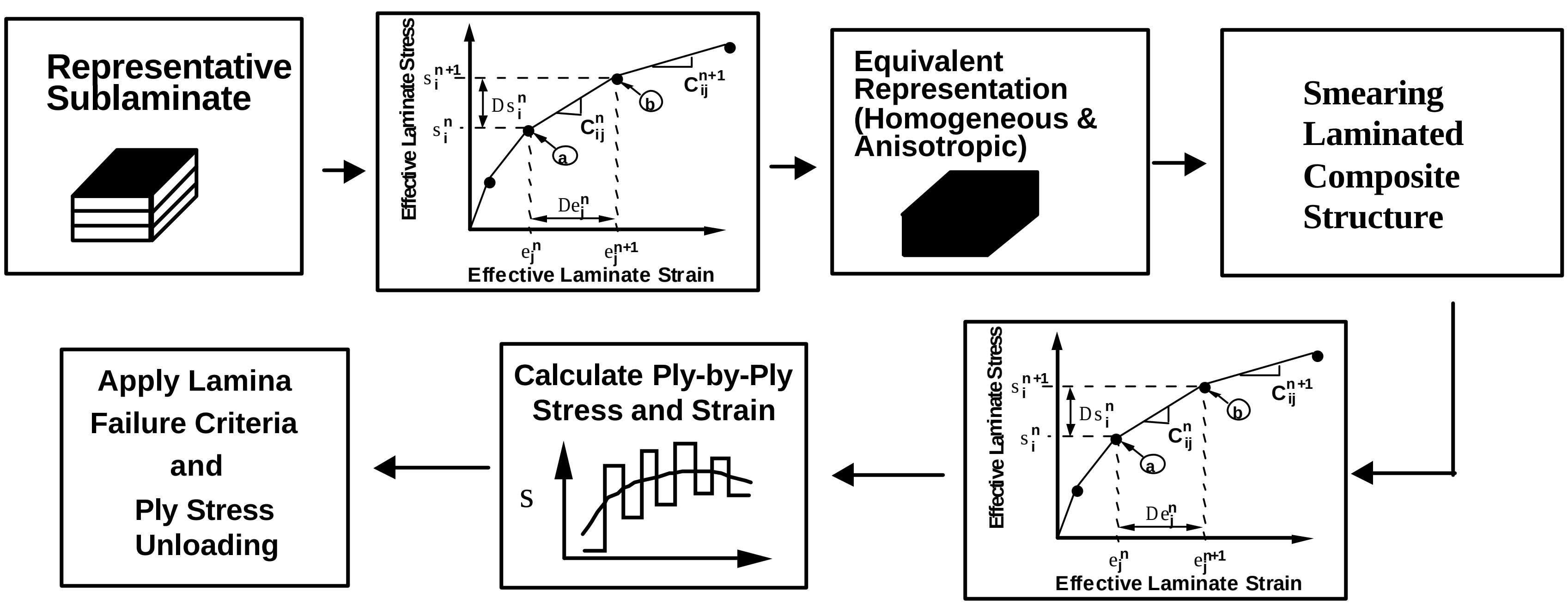
Predicted and Observed Strength and Modulus for ± 22.5 FP-alumina/Mg

Property	Temperature ºF	Calculated	Measured
Ex	70	24.5Msi	27.7Msi
Ey	70	15.3Msi	13.82
σ_L	70	74 ksi	66
σ_T	70	35.2ksi	35.2
Ex	300	23.9Msi	23.2
Ey	300	13.95	13.53
σ_L	300	74	59.6
σ_T	300	35.2	31.9

Non-linear Progressive Laminate Analysis

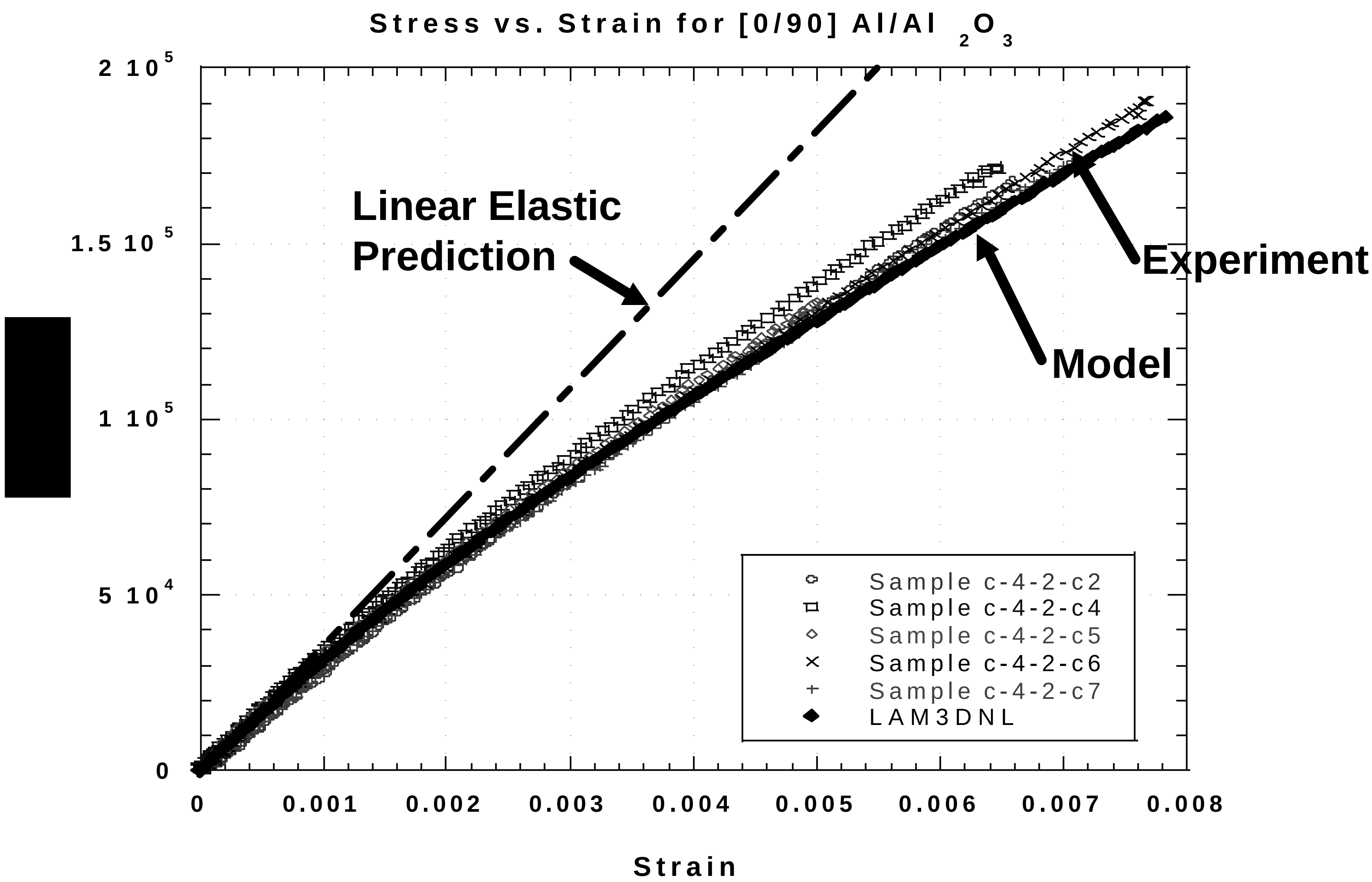
<u>Approach</u>

- Piecewise Linear Increments
- Superimposed to Form Effective Nonlinear Response
- Individual Ply Stress, Strain and Stiffness
- Ply Stress or Strain Allowables
- FEA for Structure



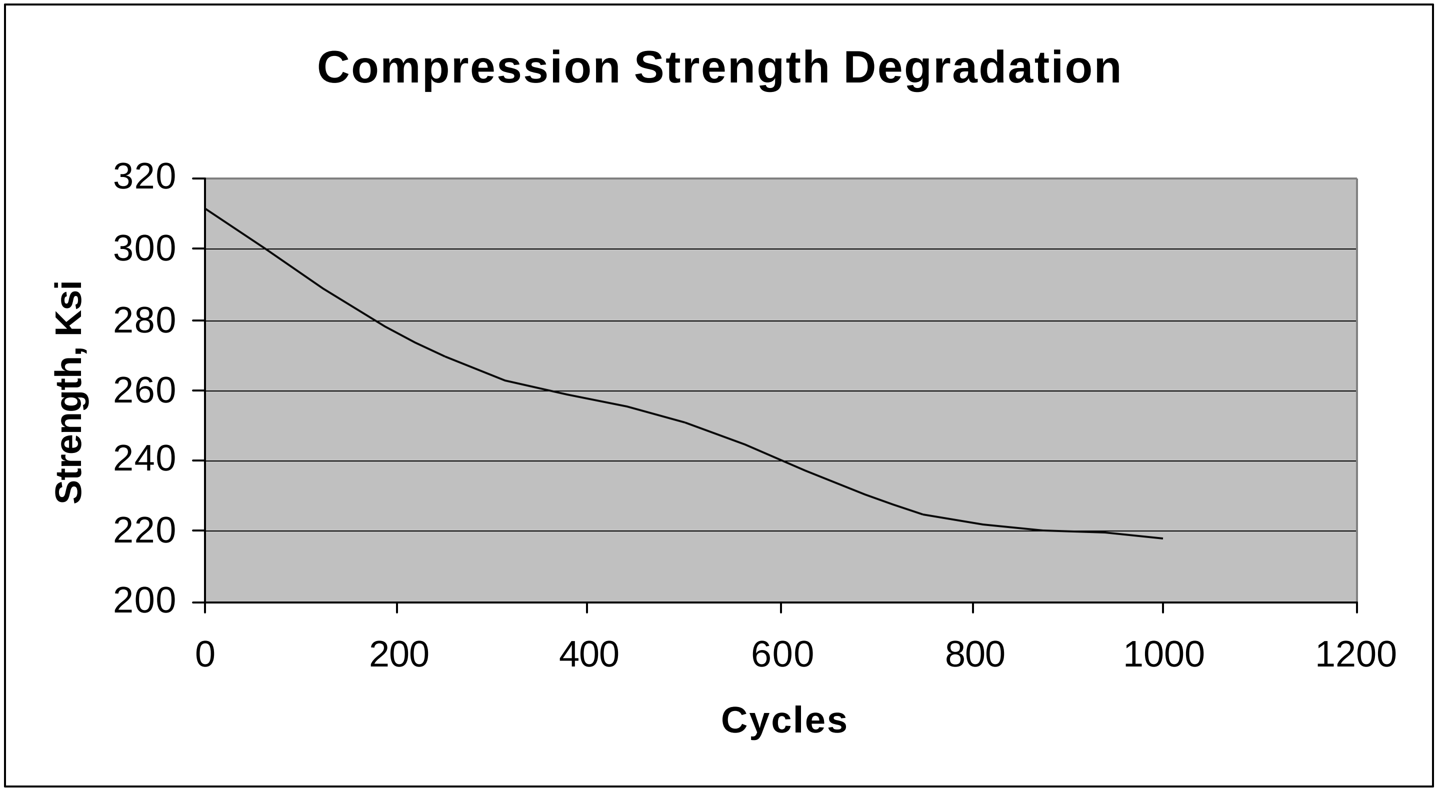
Non-Linear Laminate Predictions

Compressive stress-strain response of Al with 65% Al_2O_3 fibers with a $[0/90]_{4S}$ architecture



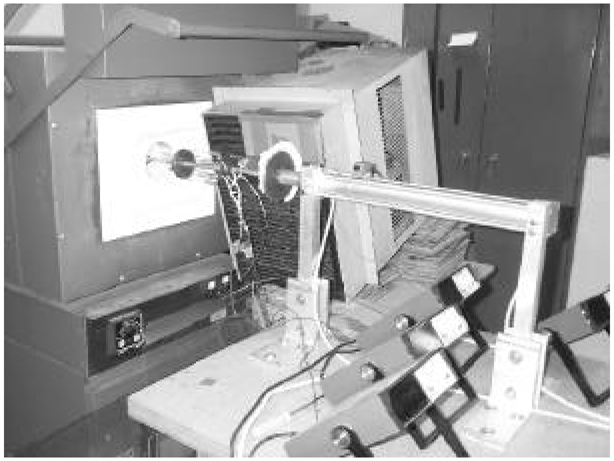
Thermal Fatigue Testing

- Testing done by LTC John Bridge at USMA
  - Specimens from 3M's automotive pushrods (commercial product)
  - Cycled at 300°C
  - Loss of 30% of compression strength after 1000 cycles
  - Matrix was Al-2wt%Cu, pure Al may behave better

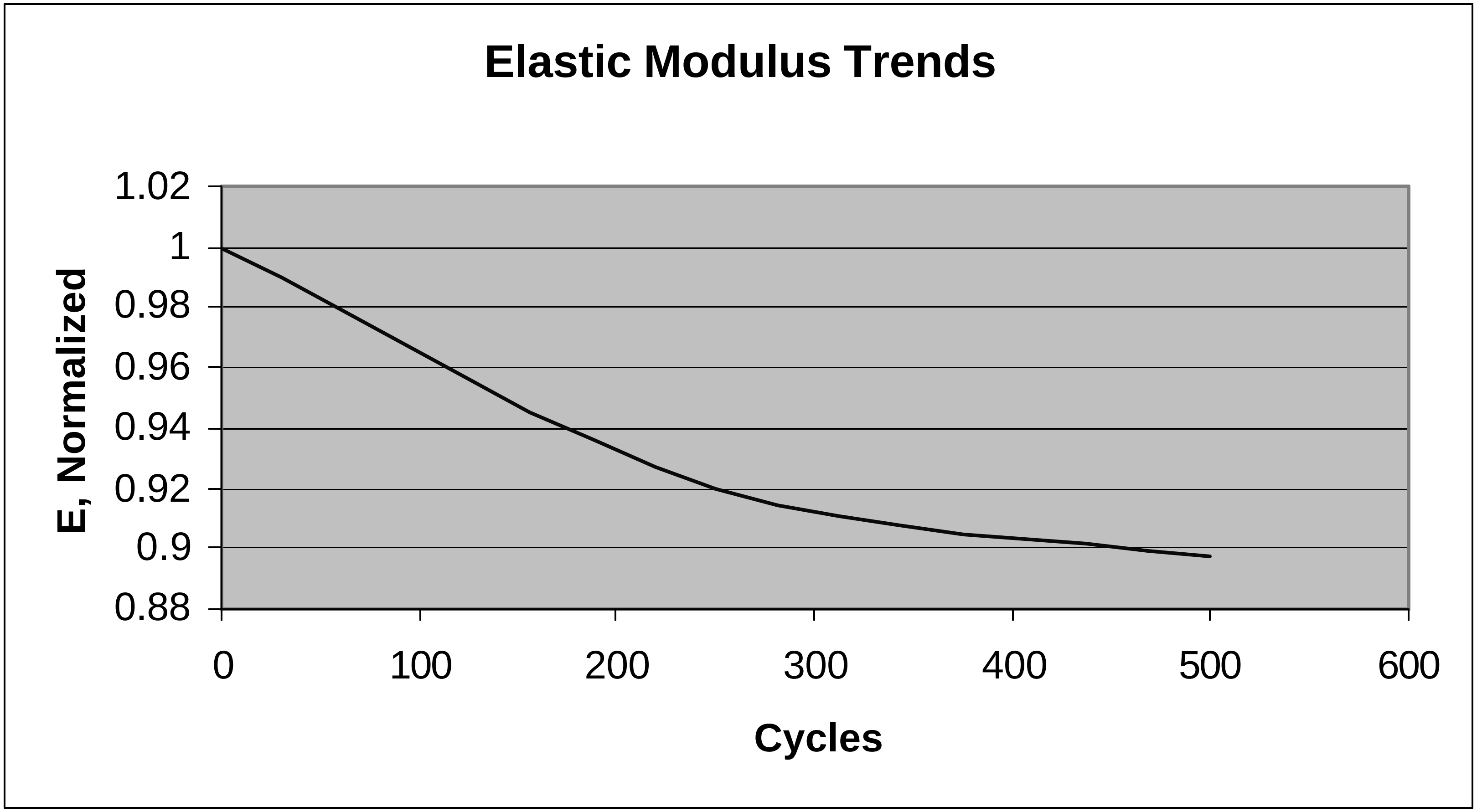


Experimental Procedures

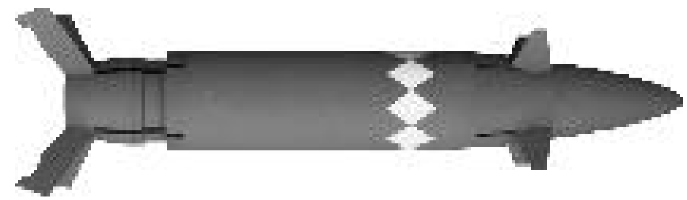
- **Specimens: 6 inch Long Hollow Rods**
  0.375 in. Wall Thickness
- **Electro-Pneumatic Piston Cycling Device**
  - Timer, Solenoids, Air Compressor, Counter, Air-Conditioner, Thermocouples, Fans
- **Specimen “Cage”**
- **Insulated Convection Furnace**
- **0 to 300 Degree C Thermal Range**
- **2.5 Minute Cycle Time**
- **250 Cycle Intervals up to 1000 Cycles**
- **Specimens Tested at each 250 Cycle Interval**



Compression Tests - Elastic

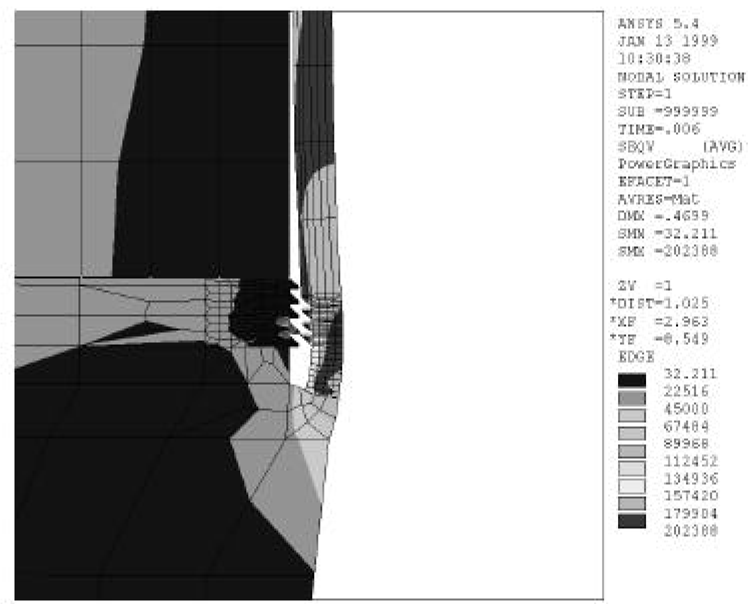


Lightweight Ordnance Metal Matrix Composites for Ordnance Applications



SADARM carrying variant of the XM982 projectile

- Exhibits excessive deformation under setback loading
- Steel shell exceeds weight goal
- Space constraints limit redesign options
- MMC shell necessary for projectile



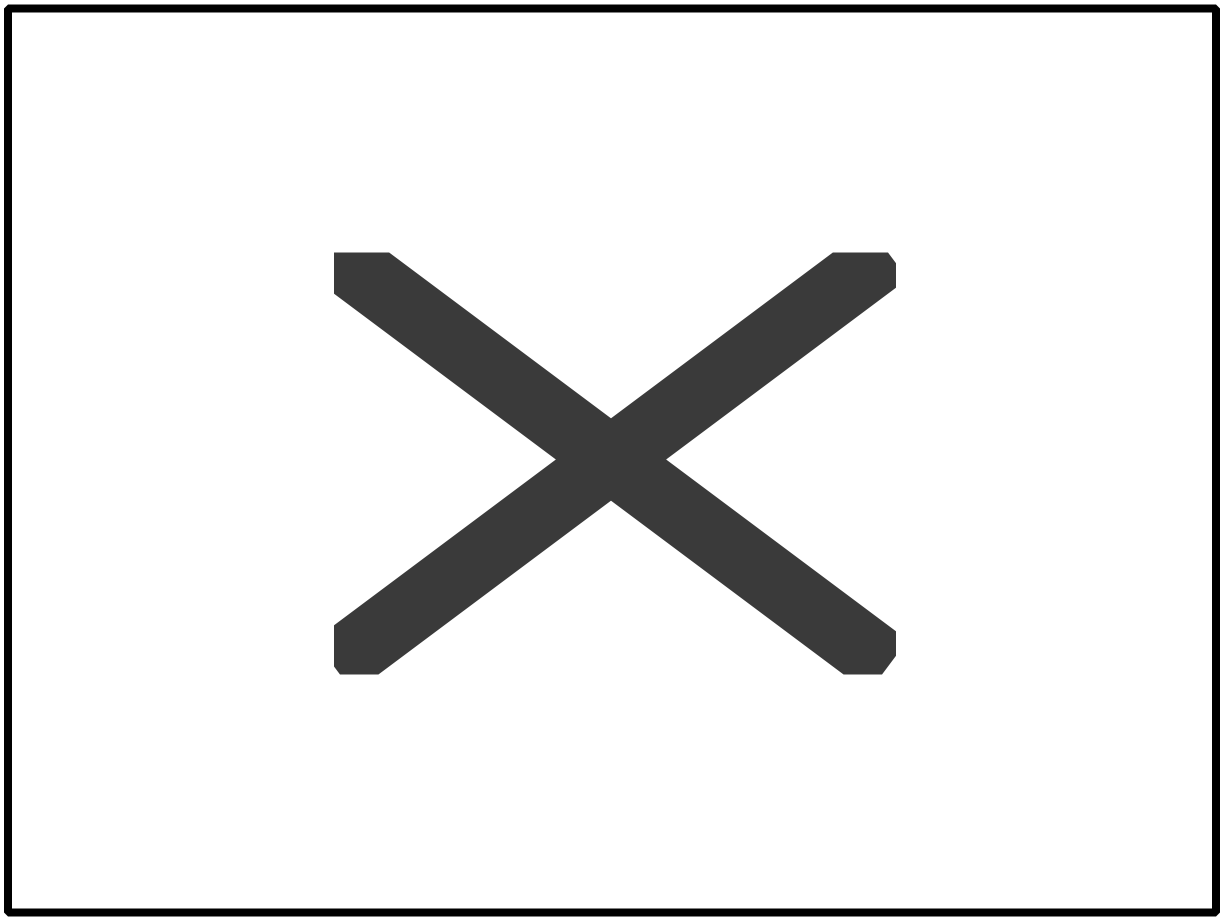
Material Impact: Artillery Shell

Comparison of an 18-in 155-mm Artillery Shell made from Steel, Aluminum Metal Matrix Composites, and Graphite/Epoxy.

Material	Shell Weight (lbs)	Weight Normalized to Steel	Available Volume (in^3)	Internal Vol. Normalized to Steel
Steel	11.95	1.00	484	1.00
AMC [0/90]	5.15	0.43	484	1.00
AS4/3501 [0/90]	7.10	0.59	400	0.83

MMC 155-mm Shell
Crush Test Results

Failure Strength, 483,000 lbs (25 lbs @ 19,300 g’s)



Conclusions

- **Metal Matrix Composites have outstanding potential for Ordnance**
  - Projectile shells 50% lighter than steel, with 67% less parasitic volume than polymer matrix composites
  - Gun barrels 50% lighter than steel

- **Modeling technologies developed to allow design for ordnance applications**
  - Lamina-level
  - Gun barrel and Projectile shell components

- **STO Program will demonstrate technology for Objective Force**
  - Develop Prototype of gun barrel or projectile shell
  - TRL 5 by 2003